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RIA R&D for Enabling Direct Neutron Cross-Section Measurements

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R&D for High Power Target and Secondary Beam Collection

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Abstract:

The expected production rates at RIA imply it should be possible to collect 10-μg of a one-day half-life isotope. The amount of material should be sufficient to enable direct neutron cross-section measurements for many unstable isotopes. This capability is crucial for many of the stockpile stewardship and some of the astrophysical cross-section measurements. Enabling this capability at RIA requires the ability to harvest the desired isotopes, process highly radioactive material into targets, and irradiate targets with neutrons. This paper will discuss the changes and additions to the RIA complex that are necessary in order to enable direct neutron cross-section measurements. This will include a discussion of harvesting as well as a conceptual design for a co-located experimental facility with radiochemistry capability and a variable "mono-energetic" neutron source.

Introduction

The stockpile stewardship program insures the reliability and safety of the US nuclear weapon stockpile without testing. It relies on state of the art simulation capabilities whose inputs include nuclear cross sections with an emphasis on neutron reaction cross sections. Nuclear cross sections play their most important role when interpreting measurements of isotope production to determine neutron and charged particle fluxes in brief intense neutron flux environments. The astrophysics community is also interested in performing neutron cross-section measurements on unstable nuclei. Both the s-process and the p-process involve neutron captures on unstable nuclei near stability. In both cases a few unstable nuclei have been measured, but most have been determined from theory alone because it has not been possible to produce enough of these isotopes to allow experiments. The Rare Isotope Accelerator changes that

The Rare Isotope Accelerator (RIA) promises the ability to make a wide variety of isotopes throughout the chart of the nuclides. Of most interest to the nuclear physics community are those far from stability that cannot be produced by any other facility. But RIA also promises never before achieved production rates of near stability nuclei. Both of these capabilities offer opportunities to make cross section measurements that were not possible before. For nuclei with a half-life of one day or more, targets can be made and irradiated with neutrons. Stewardship is therefore interested in RIA and developing the necessary infrastructure to allow the desired nuclear cross section measurements to occur.

Neutron Cross-Section Measurements at RIA

The first step in performing neutron cross-section measurements is the production and collection of the wanted isotopes. RIA promises a production rate of 10^{11}-10^{12} pps for near stability isotopes. At these rates it should be possible to collect 10 micrograms for an isotope with a one-day half-life. Presently, both the fragmentation beam line and the ISOL system are being studied for harvesting possibilities. The ISOL system offers the most straightforward means for harvesting, since mass separated radioactive ion beams are produced with beam energy of 60 keV. The fragmentation beam line is more challenging because of the purity required and the nuclei are produced at several hundred MeV per nucleon. The IGISOL system handles the stopping of the fragmented beam particles, put the predicted production limit (10^9 pps) is low compared to what is needed for harvesting. Additionally, the possibility or redirecting the beam at the first stripper of the driver linac is also being pursued. More work in this area is required.

A 10-microgram sample of an isotope with a mass number 100 and a half-life of one day corresponds to around 15 Curies of activity. Thus, a radiochemistry facility must be located at RIA capable of handling 100's of Curies of activity and processing the material into a target suitable for neutron irradiation. Hot cells capable of handling 1 kCi of hard gamma activity are not uncommon and techniques have been developed for handling such material. The chemistry facility may also need to handling the target after irradiation and separate out the desire products for measurements.

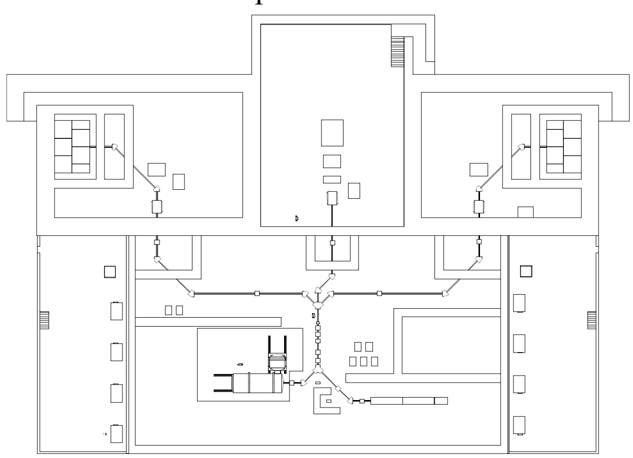

Figure 2: A drawing of a possible design for a neutron production facility at RIA. The experimental areas are up top, with a low energy neutron area in the middle. The two rooms on either side at the bottom are areas for radiochemistry. See text for other details.

In most cases, 10 micrograms of material should be sufficient to perform neutron cross-section measurements. The exact minimum amount will depend on the details of the nucleus, the desired output channel, and the method of measurement. It also depends on the neutron flux. Presently it is assumed delivering 10^{10}-10^{11} neutrons per cm^2 per second on target will be possible. The achievable neutron flux will also be a function of the desired neutron energy. For stockpile stewardship, cross-section data from 50 keV up to 20 MeV are of interest, with different reaction being important at different energies. But given the half-life of the material it will be important to have the neutron source on the RIA site. Figure 2 is a conceptual layout of such a neutron source facility. It has locations for doing radiochemistry on either side and three experimental halls for doing experiments. At the heart of the facility are two accelerators designed to accelerate protons and deuterons at high currents. The details of these accelerators and reasons why are discussed below.

Neutron Producing Reactions

There are two approaches for producing neutrons across the entire energy range of interest. A facility that produces a white source of neutrons is one, but a white source will put limitations on how the experiments are carried out since one must use methods that can distinguish between neutron energy. Also, white neutron sources of reasonable fluxes at high energies require large facilities. The other option is a tunable, "monoenergetic" neutron source. No neutron source is perfectly monoenergetic but certain reactions can be used to produce a neutron spectrum with a reasonably small energy spread. Unfortunately, no one single reaction is suitable for producing neutrons across the entire energy range. Table 1 lists several reactions that could be used to make neutrons and the energy range in which it works the best. Notice that all these reactions involve either beams of protons or deuterons.

For neutrons below about 200 keV, it is hard to make an intense beam of monoenergetic neutrons. First, a significant fraction of the beam energy is lost in a short distance (2.1 MeV protons stop in 180 microns of lithium), which causes the width of the neutron energy distribution to be large compared to 100 keV. Minimizing the energy spread will mean a thin target, which reduces the neutron flux. This can be recovered only somewhat by increasing the beam current before beam power issues on target become important. Another way to overcome these difficulties is to use moderators to shape the neutron energy spectrum to one that is desirable [1]. It will still be broad after this shaping, but it should be possible to gain some information about neutron cross-sections at these energies. If the beam is pulsed, then time of flight techniques can be used in the experiment to determine neutron energy [2]. While this becomes problematic for higher energy neutrons, this technique may still be viable at lower energy ranges, as only modest distances would be needed to distinguish neutrons of different energies.

Both the $^{7}Li(p,n)^{7}Be$ and the $^{3}H(p,n)^{3}He$ reactions work well for producing neutrons in the several hundred keV range. The lithium reaction has the practical advantage of not needing a tritium target, but unfortunately ^{7}Be has an excited state at 429 keV that results in a bimodal neutron distribution from these reactions. The $^{3}H(p,n)^{3}He$ reaction does not have this problem and could be used to make neutrons up to a few MeV.

Somewhere between 3 and 4 MeV, it becomes practical to use the $^{2}H(^{2}H,n)^{3}He$ reaction. This reaction has a positive Q value which gives the neutron about 3 MeV more energy than the incoming deuteron beam. The neutron is emitted isotropically at the lower beam energies, though there is forward focusing due to kinematics as the beam energy increase. Once the deuteron beam energy rises above 2.2 MeV, deuteron breakup can occur. Initially this will be a much smaller contribution to the neutron flux than the fusion reaction, but when the deuteron beam energy reaches 9 MeV, the yield from deuteron breakup will equal the yield from the fusion reaction [3]. Fortunately, there is a significantly large gap in neutron energies. The fusion reaction at this energy produces a sharp peak of neutrons around 12 MeV while the breakup reaction produces a neutron spectrum with a peak at 4 MeV and with a FWHM of 1 MeV. Depending on the reaction of interest this still may be a useable spectrum, especially if the threshold for the reaction lies between the two neutron distributions. Even though this type of bimodal distribution persists even at higher deuteron beam energies, but this reaction has been used to produce neutrons at energies up to 16 MeV [4] and it should be possible to go higher.

For neutrons above 14 MeV, the $^3H(^2H,n)^4He$ reaction become a possible production reaction. The production cross-section peaks near 5 barns at a deuteron beam energy of 120 kV, which is why this reaction has been used in the past for producing 14 MeV neutrons [5]. The cross-section falls quickly to 0.2 barns at a beam energy of 1 MeV. By contrast the cross-section for the $^2H(^2H,n)^3He$ reaction peaks around 0.1 barns near a deuteron beam energy of 1.6 MeV falling slowly with increasing energy so that at 10 MeV the cross-section is still about 0.08 barns. The disadvantages of using the $^3H(^2H,n)^4He$ reaction are the need for a tritium target and the lack of focusing due to kinematics compared to using $^2H(^2H,n)^3He$.

It is also possible to consider using the deuteron breakup reaction to produce neutrons. As mentioned earlier, the neutron energy distribution from this reaction will be much broader then the other reactions mentioned above. One would use a much heavier target than the deuteron, because the coulomb field would be much higher and neutrons from fusion and transfer reactions would be much less a factor.

The Accelerators

As noted above, all the reactions involve a beam of either deuterons or protons at low energies. Since, the neutron flux is directly proportional to beam intensity, maximizing beam current is desirable. Thus, at the heart of this neutron source facility must be one or more low energy, high current accelerators for light ions. There are several options for the choice of accelerator all with advantages and disadvantages. Due to the combination of high current and energy variability, it was found that not one machine adequately met all the criteria. Thus, the present design includes two, a 3 MeV dynamitron and a 30 MeV linac.

A dynamitron has been used before as a neutron source [6] and is presently a commercially available system [7]. A dynamitron rectifies an RF power system to create a DC acceleration potential up to much as 5 MV depending on the system. A dynamitron also offers high average beam currents, up to tens of milliamps, depending on the voltage. Thus, the dynamitron becomes an attractive system for producing low energy neutrons. In addition to providing a DC neutron source, it has also been used as a pulse neutron source [8], which will be necessary if an experiment needs to use time of flight to distinguish neutron energy.

In order to reach higher neutron energies, a higher energy beam is needed. Though there are several options, the current approach being evaluated is a linac. The linac would start with a 1-2 MeV RFQ followed by multiple, short, independently-driven DTL modules each capable of adding another ~1 MeV of acceleration per unit. As the modules would be short, the velocity acceptance of each section is broad, allowing transport, acceleration, bunching, and longitudinal focusing over a variety of beam energies. This configuration allows the linac to be more energy variable than a conventional RF linac designed for high efficiency, and thereby facilitates a tunable neutron source. The linac should be able to provide several hundred microamps of average beam current and would be designed for a species with a charge to mass ratio of one-half, allowing operation with molecular hydrogen, deuterium, alphas, and similar species.

Summary

The stockpile stewardship program is interested in neutron cross sections on many unstable nuclei. The Rare Isotope Accelerator promises the capability of producing unstable isotopes in sufficient quantities allowing neutron cross-section measurements. Thus, the stockpile stewardship community is very interested in RIA and insuring the correct infrastructure is present to allow direct neutron measurements. These include the ability to collect the appropriate isotope, process the material into to a target at a radiochemistry facility, and irradiate the target with neutrons at a separate but co-located neutron source. This neutron source must be able to deliver high neutron fluxes on target for neutron beam energies from around 50 keV to 20 MeV. It will do this with two, high current, low energy, light ion accelerators providing beams appropriate for several different nuclear reactions. The final specifications of these pieces are still being developed and we are working with the rest of the RIA community to develop these ideas. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng- 48.

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